

Design and Performance Evaluation of an Off-Grid Solar Powered LED Lighting System for Tower Hydroponic Cultivation

Renny Eka Putri*, Siti Nurhaliza, and Omil Charmyn Chatib

Department of Agriculture Engineering and Biosystem, Universitas Andalas, Padang, 25163 West Sumatera, Indonesia

ABSTRACT

The rapid increase in urbanisation has led to a reduction in productive agricultural land, driving the need for modern agricultural innovations that are efficient and environmentally friendly. This study aims to design an LED grow light system using solar power to support the growth of pak choy (*Brassica rapa* L.) plants using the hydroponic tower system (HTS) method in a greenhouse. This solar power system utilises the potential of solar energy in the Lubuk Alung area, Padang, West Sumatra, Indonesia. The study was conducted by comparing plant growth between the LED grow light system treatment and control plants without an LED. The parameters observed included plant height, leaf length, leaf width, and number of leaves. This system integrates natural light with artificial lighting from LEDs for 3 hours at night to extend the duration of plant photosynthesis. The maximum sunlight intensity is 1180.26W/m² with an electrical power generated around 3045.07 watts. The average solar panel efficiency reaches 20% with peak power occurring at 11:00-12:00 WIB. The results showed that plants supplemented with LED lighting exhibited significantly better growth than control plants. Analysis indicated that this system requires a relatively high initial investment but has potential benefits through increased productivity and pesticide-free crop quality. This research proves that the use of renewable energy in modern agricultural systems can be a practical, efficient, and sustainable solution to meet food needs in urban areas.

Keywords: Energy efficiency, *greenhouse*, hydroponics, LED grow light, pak choy, solar panel

ARTICLE INFO

Article history:

Received: 18 July 2025

Accepted: 05 January 2026

Published: 19 March 2026

DOI: <https://doi.org/10.47836/pjtas.49.S1.04>

E-mail addresses:

rennyekaputri@ae.unand.ac.id (Renny Eka Putri)

siti_nurhaliza@gmail.com (Siti Nurhaliza)

omilcchatib@ae.unand.ac.id (Omil Charmyn Chatib)

* Corresponding author

INTRODUCTION

The rapid increase in the world's population has put increasing pressure on natural resources. (Abu Hatab et al., 2019). By 2050, it is estimated that around 68% of the population will live in urban areas, with

Indonesia projected to reach an urbanisation rate of 66.6% by 2035 (United Nations, 2019). This increase in urbanisation creates various problems in several food sectors, one of which is an increase in food demand that is faster than the increase in production (Arifin et al., 2019). Therefore, one solution that can help overcome this challenge is the development of efficient and environmentally friendly agricultural technology (Abu Hatab et al., 2019). Hydroponics is a growing method that is increasingly being applied due to its ability to increase the efficiency of water and nutrient use, as well as minimise the use of pesticides (Chatterjee et al., 2025; Putri et al., 2023). The use of greenhouses can control environmental conditions that are suitable for optimising plant growth, while hydroponic techniques minimise land use and maximise water and nutrient efficiency (Putri et al., 2025; Yusuf et al., 2025). The cultivation system with the hydroponic tower system (HTS) allows the cultivation of pak choy on a vertical scale, thus maximising the use of limited land in urban areas (Al-Kodmany, 2018). The Tower Hydroponic system offers advantages, including efficient water and nutrient use, improved aeration of plant roots, and increased planting density per unit area (Putri et al., 2025). Due to its vertical configuration, this system is particularly suitable for controlled environments and limited land conditions. In this study, the tower hydroponic system was employed as the plant cultivation platform to evaluate system performance under controlled nutrient delivery and environmental conditions (Barbosa et al., 2015).

Pakcoy (*Brassica rapa L.*) is a vegetable with high protein and vitamin content that is suitable for cultivation using hydroponic systems. However, plant growth in greenhouses is greatly influenced by light availability (Xin et al., 2019). Indonesia, located in a tropical region with natural sunlight varying seasonally and daily, is often below the optimal requirements for continuous photosynthesis (Parker et al., 2019). Insufficient light intensity or duration can inhibit the rate of photosynthesis, reducing biomass accumulation and overall crop yields (Zou et al., 2025). LED grow light is one of the effective and efficient artificial lighting solutions for hydroponic plants. (Bantis et al., 2020). Full-spectrum LEDs with a Photosynthetically Active Radiation (PAR) range of 400-700nm can replace sunlight as a production source for plants (Huché-Thélier et al., 2016). However, the use of LED grow lights requires high electrical energy consumption. To overcome this problem, in this study, the electricity needs from the State Electricity Company (PLN) of Indonesia were replaced by the use of solar panels to meet electricity needs. The integration of LED grow lights with solar power represents a sustainable approach to reducing dependency on fossil fuels and minimising operational costs in greenhouse agriculture. Indonesia, as a tropical country, has significant solar energy potential that can be harnessed to support agricultural systems, especially in regions with high solar irradiance such as West Sumatra. The utilisation of solar-powered LED lighting not only enhances plant growth but also contributes to environmentally friendly and low-emission agricultural practices (Al-Shamani et al., 2016).

To address energy consumption challenges in controlled-environment agriculture, the application of solar photovoltaic systems in greenhouse operations has emerged as a sustainable and environmentally friendly solution. Indonesia, located in the tropical region, has significant solar energy potential with an average solar radiation ranging from 4.5 to 5.1 kWh/m²/day, making it suitable for solar-based agricultural applications (Gholami et al., 2025). Previous studies have demonstrated that greenhouse systems powered by solar photovoltaic energy can substantially reduce dependence on grid electricity while maintaining stable microclimatic conditions necessary for plant growth (Al-Shamani et al., 2016; Hassanien et al., 2016). The integration of renewable energy into greenhouse systems also contributes to reduced operational costs and lower carbon emissions, supporting long-term agricultural sustainability. Therefore, this study aims to design and evaluate a solar panel-powered LED grow light system integrated with a Hydroponic Tower System (HTS) to enhance the growth of pak choy (*Brassica rapa* L.) under tropical greenhouse conditions. The proposed system combines natural sunlight with supplemental LED lighting powered by solar energy to extend the daily photoperiod and improve photosynthetic activity. This research is expected to contribute to the development of sustainable urban agriculture by providing a replicable and energy-efficient vertical farming model that supports increased crop productivity while minimising reliance on conventional grid electricity.

MATERIALS AND METHODS

The materials and methods of this study were carried out through a series of well-defined research stages to ensure systematic implementation and reliable results. The experiment was conducted at a specific experimental location under greenhouse conditions, which served as the controlled environment for the study. The first stage involved the setup of the hydroponic tower system (HTS) as the primary plant cultivation unit, followed by the installation of LED grow lights to provide supplemental artificial lighting. Subsequently, a solar photovoltaic system was designed and integrated to supply electrical power for the LED lighting system and supporting components. Pak choy (*Brassica rapa* L.) plants were selected as the plant material and cultivated under controlled growing conditions, including nutrient solution composition, irrigation scheduling, and photoperiod management. The final stage consisted of data collection and analysis, where plant growth parameters such as plant height, leaf length, leaf width, and number of leaves were measured and statistically analysed to evaluate the effects of the integrated hydroponic, lighting, and solar energy systems.

Experimental Location

This experiment was conducted in a greenhouse located in Lubuk Alung District, West Sumatra, Indonesia, with the coordinates -00°67'8122", 100°28'043". This research was

conducted from November to December 2024. In that month, the DNI data recorded in the Lubuk Alung area were 78.3 kwh /m² and 85.8 kwh/m². The DNI value this month is relatively low compared to the data in the previous month. This is influenced by the large number of clouds covering the area. The greenhouse is constructed using a light steel frame with UV-resistant polyethylene sheets for the roof and walls, combined with insect-proof netting. This series was made in a greenhouse (GH). The greenhouse measures 5.85 meters long, 4.30 meters wide, and 2 meters high. Its roof is triangular, measuring 5.85 meters long, 4.60 meters at the base, and 1.05 meters high (Figure 1).

Hydroponic Tower System (HTS) Setup

The HTS system was built using a hydroponic tower system made of 4-inch PVC pipe and a height of 125 cm. The pipe has 26 holes on the sides, and the holes are spaced 15 cm apart. The pipe is positioned vertically. A nutrient film technique (NFT) recirculation system is used, where a submersible pump flows the nutrient solution from the storage tank to the top of each tower, allowing the solution to drip through the plant roots before returning to the tank, as shown in Figure 2.

LED Grow Light Installation

The duration of LED exposure to plants can be determined by first calculating the average photosynthetic photon flux density (PPFD), which represents the amount of photosynthetically active radiation received by the plant canopy per unit time. The relationship between light intensity and exposure duration is expressed using the Daily Light Integral (DLI), which quantifies the cumulative number of photosynthetically active photons received per unit area per day. As shown in Equation (1), DLI is obtained by multiplying the

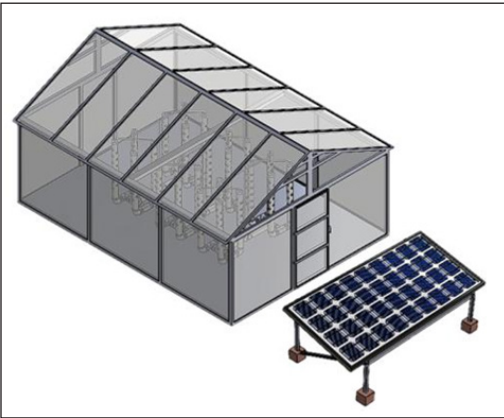


Figure 1. Greenhouse and hydroponic tower

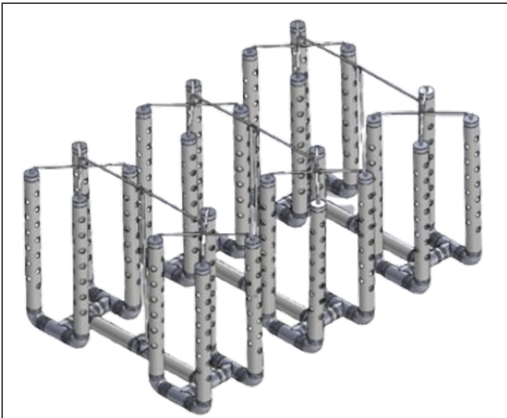


Figure 2. Overview of tower hydroponic system

average PPFD by the light exposure time, providing a practical metric for evaluating whether plants receive sufficient light for optimal photosynthesis (Faust, Logan, & Heins, 2005). This approach is widely applied in controlled-environment and greenhouse agriculture to optimise artificial lighting strategies, particularly when using LED systems. By adjusting the photoperiod based on measured PPFD values, the target DLI for leafy vegetable growth can be achieved while avoiding excessive light input and unnecessary energy consumption (Mitchell et al., 2015; Pennisi et al., 2019).



Figure 3. LED position on HTS

The selection of the type of LED lamp is based on the light spectrum that suits the photosynthesis needs of plants. The specifications of the lamp used are *full-spectrum LED* grow light strips or LEDs with a complete spectrum because they cover the entire PAR (*Photosynthetically Active Radiation*) light spectrum. The full spectrum LED used has white light with a CCT (Correlated Colour Temperature) of 5700K with a power of 15watts. This LED lamp has a light beam range of 120×30 cm. Positioning greatly influences the results of the study (Pereira, 2025). The optimal LED exposure time for pakcoy plants is 14 hours. LED calibration testing was carried out using four lamps placed at a distance of 15 cm from the plants with a grid size of $22.5 \text{ cm} \times 15 \text{ cm}$ (Figure 3).

The duration of LED exposure to plants can be determined by first finding the average PPFD value. To find the average PPFD value, use the following Equation 1:

$$DLI = \text{Average PPFD} \times \text{exposure time} \quad [1]$$

where:

DLI = Daily Light Integral ($\text{mol m}^{-2} \text{ day}^{-1}$)

PPFD = Photosynthetic photon flux density ($\mu\text{mol m}^{-2} \text{ s}^{-1}$)

Solar Photovoltaic System Design

Solar panels are the main element in a solar power plant system which plays a role in converting solar energy into direct current (DC) electricity (Putri et al., 2025). In this design, the PLTS system is designed using an *Off-Grid configuration*. This *Off-Grid* System aims to supply electrical power needs, both in the form of direct current (DC) and alternating current (AC). This system consists of a 550 Wp monocrystalline solar panel, a 100 Ah

VRLA battery, a 20 A solar charge controller, and a pure sine wave inverter. Daily electrical energy requirements (Et) are calculated using the following Equation 2.

$$Et = (P \times t) \tag{2}$$

where:
P = Load power consumption (W)
t = Operational time (hours)

Table 1
Daily electrical energy requirements for greenhouse operations

Electrical Load	Amount	Load Capacity (watts)	Operating Hours (Hours)	Power Requirement (Wh)
Pump	4	36	12	1728
Spraying	1	60	0.23	13.8
Exhaust Fan	1	45	6	270
Light	8	15	3	360
Total Power Requirement (Wh)				2371.8

The required solar panel capacity is estimated using Equation 3.

$$SP = Et/Tmax \tag{3}$$

where:
SP = Solar panel capacity (Wp)
Tmax = Effective sunshine hours (hours)

Based on the calculation of daily energy requirements and an average of 5 hours of sunlight/day, the minimum capacity required is 474.36Wp; therefore, a panel with a capacity of 550Wp was selected.

Plant Materials and Growing Conditions

Pakcoy (*Brassica rapa L.*) was germinated in rockwool cubes for 10 days before being transferred to the HTS. The nutrient solution was prepared using the AB Mix formula, with electrical conductivity (EC) maintained at 1.5-2.0mS /cm and pH adjusted to 6.0-6.5. Two treatments were established: LED-assisted system - plants receiving supplemental LED lighting and Control - plants receiving only natural sunlight.

Data Collection and Analysis

Plant growth parameters (height, leaf length, leaf width, and number of leaves) were measured every 3 days for 27 days after planting (DAP). Statistical analysis was performed using a two-tailed independent t-test at a 95% confidence level ($p < 0.05$). Environmental parameters inside and outside the greenhouse (temperature, relative humidity, light intensity) were recorded using a data logger.

RESULTS

The results present and interpret the performance of the integrated hydroponic tower system equipped with solar-powered LED lighting. The discussion begins with the results of LED light and photoperiod calibration, which are critical for ensuring appropriate light intensity, spectral suitability, and photoperiod duration to support optimal photosynthesis in leafy vegetables (Bantis et al., 2018; Pennisi et al., 2019). This is followed by an analysis of the solar panel energy potential, focusing on solar irradiance availability, power generation characteristics, and system reliability in meeting nighttime lighting demands, as commonly evaluated in photovoltaic-powered greenhouse systems (Duffie & Beckman, 2013; Hassanien et al., 2016). Finally, plant growth observations are discussed based on measured vegetative parameters to assess the response of pak choy growth to supplemental LED lighting and renewable energy integration, as reported in previous hydroponic and controlled-environment agriculture studies (Mitchell et al., 2015; Resh, 2013).

LED Light and Photoperiod Calibration

The LED light and photoperiod calibration were performed to ensure uniform light distribution and adequate light intensity for optimal pak choy growth. Based on previous studies, the optimal daily light exposure for pak choy plants is approximately 14 hours; therefore, the photoperiod in this study was set accordingly. Calibration tests were conducted prior to the experiment to verify that the LED system delivered consistent and sufficient illumination across the plant canopy. Four LED lamps were installed at a distance of 15 cm above the plants to achieve effective light penetration and minimise shading effects. Light intensity measurements were carried out using a lux meter arranged in a measurement grid with a spacing of 22.5 cm × 15 cm to represent the planting layout. The recorded illuminance values were used to evaluate the spatial uniformity of light distribution across the hydroponic tower system. Since lux values do not directly represent photosynthetically active radiation, the measured data were converted into photosynthetic photon flux density (PPFD) values using the Waveform Lighting conversion tool (www.waveformlighting.com). The resulting PPFD values, presented in Figure 4 and 5, were used to confirm that the LED lighting system met the light requirements for vegetative growth of pokchoy.

271 1.1	246 2.1	211 3.1	203 4.1
1863 1.2	2208 2.2	3735 3.1	2973 4.2
2689 1.3	3250 2.3	6235 3.3	7190 4.3
2739 1.4	4858 2.4	7180 3.4	7681 4.4
2550 1.5	4550 2.5	7246 3.5	8070 4.5
3218 1.6	6018 2.6	7220 3.6	7878 4.6
2522 1.7	5040 2.7	7659 3.7	6890 4.7

Figure 4. LED lux meter measurement data at a distance of 15 cm from the plant

6,23 1.1	5,66 2.1	4,85 3.1	4,67 4.1	1.1	2.1	3.1	4.1
42,85 1.2	50,78 2.2	89,91 3.1	68,38 4.2	1.2	2.2	3.2	4.2
61,85 1.3	74,75 2.3	143,41 3.3	165,37 4.3	1.3	2.3	3.3	4.3
63 1.4	111,73 2.4	165,14 3.4	176,66 4.4	1.4	2.4	3.4	4.4
58,65 1.5	104,65 2.5	166,66 3.5	185,66 4.5	1.5	2.5	3.5	4.5
74,01 1.6	138,41 2.6	166,06 3.6	181,19 4.6	1.6	2.6	3.6	4.6
58,01 1.7	115,92 2.7	176,16 3.7	157,55 4.7	1.7	2.7	3.7	4.7

Figure 5. PPFD values from LED calibration tests

The duration of LED exposure for plants can be determined by first calculating the average PPFD value using the following Equation 4.

$$\bar{x} = \sum \frac{x_i}{n}$$
$$\bar{x} = \frac{2.827,81 \frac{\mu mol}{s} / m^2}{35}$$
$$= 80.79 \mu mol / s / m^2$$

[4]

where:

$\bar{x}$: Average PPFD ($\mu\text{mol/s/m}^2$)

X_i : PPFD value at each grid point

N : total number of grid points

After obtaining the average PPFD value, the Daily Light Integral (DLI) can be calculated using the following Equation 5.

$$\text{DLI} = \text{Average PPFD} \times \text{exposure time}$$

$$\text{DLI} = 80.79 \mu\text{mol/s/m}^2 \times 3600 \text{ s/hour}$$

$$= 290.844 \mu\text{mol/m}^2/\text{hour} \times 1/1,000,000 \quad [5]$$

$$= 0.290844 \text{ mol/m}^2/\text{hour} \times 14 \text{ hours}$$

$$= 4.0718 \text{ mol/m}^2/\text{day}$$

Based on the calculated DLI value, the LED lighting photoperiod can then be determined using the following Equation 6.

$$\text{Fp} = \frac{\text{DLI}}{\text{PPFD} \times 0,0036}$$

$$\text{Fp} = \frac{4,0718}{80,79 \times 0,0036}$$

$$\text{Fp} = \frac{4,0718}{0,290844} \quad [6]$$

$$= 13,999 \approx 14 \text{ hours}$$

Calibration of the LED grow light at a distance of 15 cm from the plant canopy resulted in an average PPFD of $80.79 \mu\text{mol m}^{-2} \text{ s}^{-1}$. Based on Equation 1, the Daily Light Integral (DLI) achieved was $4.07 \mu\text{mol m}^{-2} \text{ day}^{-1}$ for the LED supplementation period. When combined with natural sunlight, this extended the photoperiod to 14 hours/day, allowing for longer photosynthetic activity outside of daylight hours. Figure 6 show procedure using sunlight and LED lighting. From 07.00 to 18.00, plants rely exclusively on natural

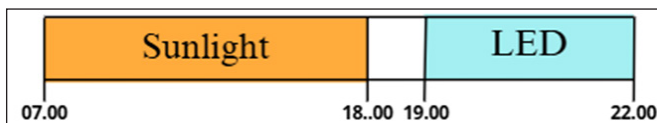


Figure 6. Supplemental lighting schedule showing the combination of natural sunlight and LED grow light periods

sunlight as the primary light source. During this period, the LED lighting system remains switched off, allowing photosynthesis to occur under natural solar radiation while reducing electrical energy consumption. From 18.00 to 19.00, a transition period without lighting is applied. This interval represents a gradual shift from daylight to darkness, simulating natural conditions. The transition phase helps prevent sudden changes in light intensity that could induce physiological stress in plants and supports a more stable photoperiodic response. From 19.00 to 22.00, LEDs are activated to provide supplemental artificial lighting. The additional illumination extends the daily light exposure and supports photosynthetic activity during the evening. After 22:00, all lighting sources are turned off to allow a complete dark period, which is essential for maintaining normal plant photoperiodism and growth regulation. This lighting strategy integrates the efficient use of natural sunlight with controlled LED supplementation to optimise plant growth while maintaining energy efficiency and a balanced light-dark cycle.

Results of Solar Panel Energy Potential Analysis

This research was conducted from November to December 2024. During those months, the recorded DNI data for the Lubuk Alung area were 78.3 kWh /m² and 85.8 kWh/m². The DNI values for these months were relatively low compared to the data from the previous month. This was influenced by the large amount of cloud covering the area. The average daily light intensity outside *the greenhouse* during the study was approximately 331.13 W /m². This figure is relatively low compared to the average normal sunlight intensity of approximately 800-1,200 W/m². Monitoring of light intensity in a greenhouse environment can be seen in Figure 7.

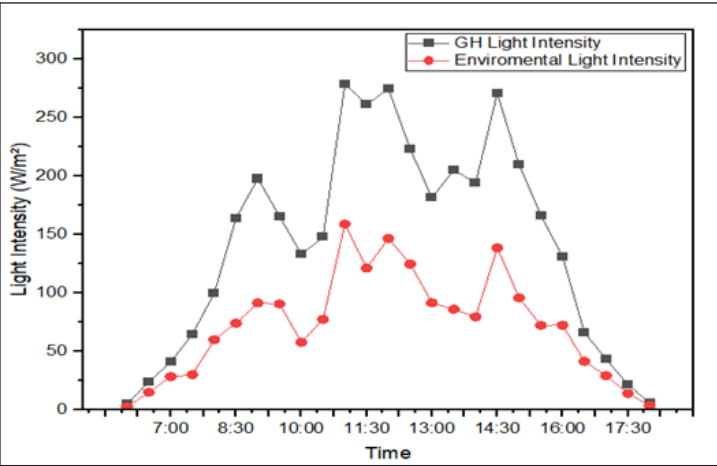


Figure 7. Greenhouse light intensity monitoring and the environment

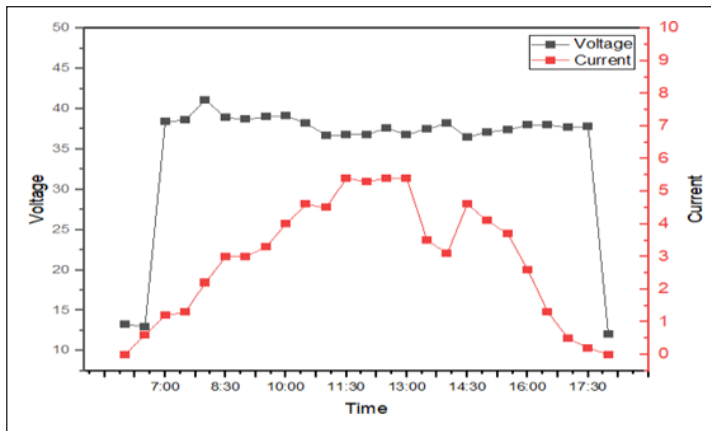


Figure 8. Hourly voltage and current output from solar panels

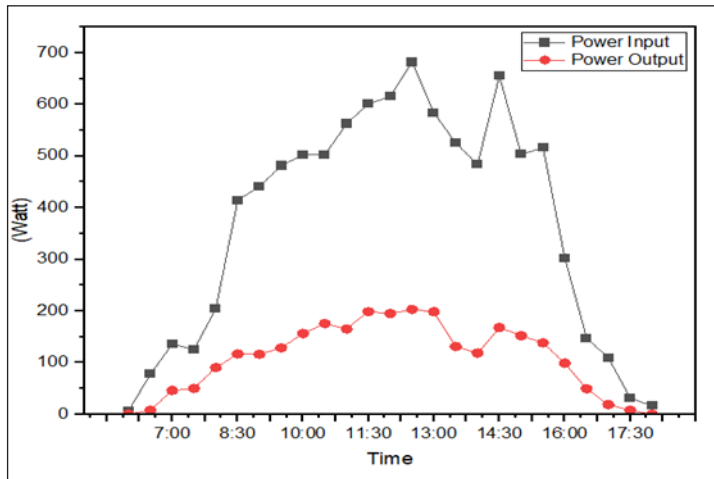


Figure 9. Daily power input and output of the solar photovoltaic system

Monitoring of the solar photovoltaic system was carried out from 06:00 to 18:00 during which time the peak output occurred between 11:00 and 12:00, this coincided with the maximum level of solar irradiation. The average charging efficiency of the solar photovoltaic system was 82 %, with a maximum instantaneous efficiency of 89% during optimal sunlight conditions. Monitoring of the solar photovoltaic input and output power can be seen in Figure 8 and 9.

Based on the three graphs above, it can be seen that there are differences in current and voltage values for each period. Voltage tends to appear more stable than current because current is primarily influenced by sunlight intensity (irradiance), while voltage is more sensitive to changes in temperature and load conditions (Figure 10). The 100 Ah VRLA

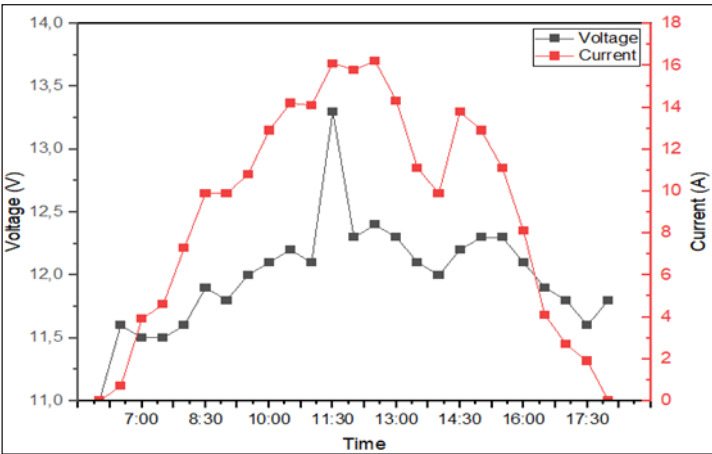


Figure 10. Monitoring of battery voltage and current during a 24- hour cycle

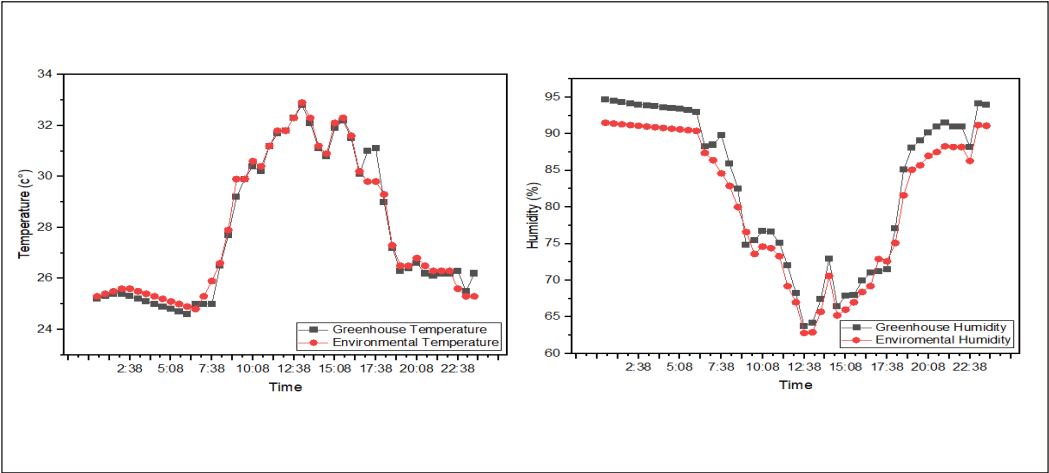


Figure 11. Humidity inside and outside the greenhouse

battery maintained a stable discharge, enabling the LED system to operate at night. The State of Charge (SOC) remained above 60% throughout the test, demonstrating sufficient capacity for the designed load (Skoplaki, E., & Palyvos, J. A.,2009; Villalva et al., 2009).

The average temperature monitoring inside the greenhouse during the experiment was at $27.5 \pm 1.3^{\circ}\text{C}$, with an average relative humidity of $75.2 \pm 4.8\%$. These values remain within the optimal growth range for *Brassica rapa L.* This occurs because the *greenhouse* is equipped with *an exhaust fan* and *misting* which function to control the temperature and humidity conditions *of the greenhouse*. Temperature and humidity monitoring can be seen in Figure 11.

Plant Growth Observation

Observations of pak choy plants involved two treatments (plants in the system with LED lighting for 3 hours at night and control plants without LED lighting). The LED lighting was applied to the plants in the system from 7:00 PM to 10:00 PM WIB. The purpose of this LED lighting was to compare the growth of the plants in the system with the LED lighting compared to the control plants. Lighting is one of the environmental factors that influences photosynthesis and plant growth. In hydroponic systems, especially those used indoors or in locations with limited natural light, supplemental lighting such as LEDs is often used to support optimal plant growth. Therefore, it's important to determine whether adding LEDs for 3 hours per day can have an impact. significantly on plant growth compared to the control system. This hypothesis can be proven by the results of the plant t-test analysis in Table 10. Measurement parameters for plants include plant height, leaf length, leaf width, and number of leaves. The average values for height, leaf length, leaf width, and number of leaves at 27 DAP are summarised in Table 4. A comparative graph of the growth of Pak choy can be seen in Figure 12.

Table 2
Comparison of plant growth parameters between LED-assisted treatment and control treatment at 27 days after planting

Observed Parameters	Treatment	Average	Standard Deviation	t value	t table	Significance (p-value)
Plant Height	System	13,419	1,034	4.163	1,985	0,000
	Control	12,581	0.934			
Leaf Length	System	8,226	0.703	5,479	1,985	0,000
	Control	7,450	0.683			
Leaf Width	System	5,450	0.451	5.141	1,985	0,000
	Control	4,961	0.480			
Number of Leaves	System	12,268	1,305	10,097	1,985	0,000
	Control	10,178	0.592			

The comparison of plant growth parameters between the LED-assisted treatment and the control at 27 days after planting (DAP) was evaluated using an independent t-test, as presented in Table 4. The results indicate that all observed growth parameters, plant height, leaf length, leaf width, and number of leaves, were significantly higher in plants grown under the LED-assisted system compared to the control treatment without LED supplementation. For plant height, the LED-assisted treatment showed a higher average value (13.419 cm) than the control (12.581 cm). The calculated t value (4.163) exceeded the critical t table value (1.985), with a p-value of 0.000, indicating a statistically significant difference. Similar trends were observed for leaf length and leaf width, where

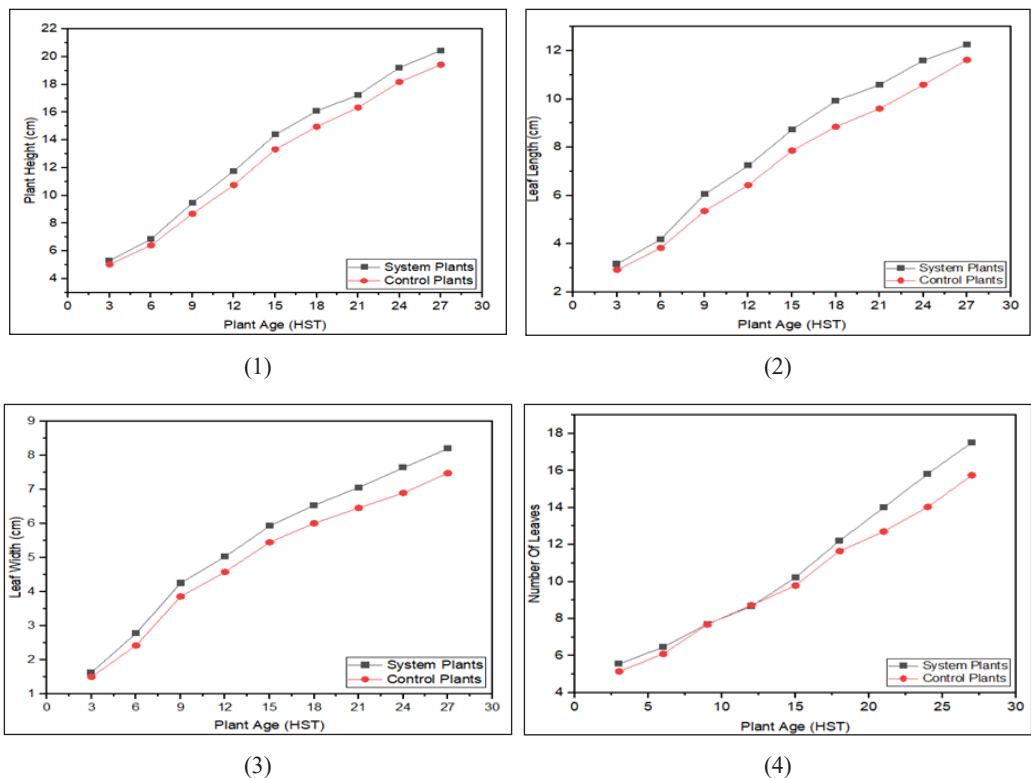


Figure 12. Graph (1) leaf length (2) number leaves (3) leaf width (4) Number of leaves during the cultivation period

the LED-assisted system produced longer and wider leaves, with *t* values of 5.479 and 5.141, respectively, both exceeding the critical value and resulting in highly significant differences ($p < 0.05$). The most pronounced effect of LED supplementation was observed in the number of leaves, where plants under the LED-assisted system achieved an average of 12.268 leaves compared to 10.178 leaves in the control. The corresponding *t* value of 10.097, far above the *t* table value, confirms a very strong statistical significance ($p = 0.000$). Overall, these results demonstrate that supplemental LED lighting significantly enhanced vegetative growth of pak choy at 27 HST, likely due to extended photoperiod and improved photosynthetic activity, thereby validating the effectiveness of the LED-assisted hydroponic tower system (Fan et al., 2019).

In the graph of the average plant height at 27 days after planting (DAP), the system plant reached a height of 20.45 cm and the average height of the control plant was 19.43 cm. The average length of pak choy leaves at 27 DAP planting age, the average leaf length of the system plant was 12.55 cm and the control plant was 11.62 cm. The average leaf width of the plant at 27 DAP, the system plant had a larger leaf width than the control

plant, which was 8.20 cm, while the control plant was 7.48 cm. The average number of leaves on the 27th day of DAP for the system plant and the control plant was 17.52 and 15.75 leaves, respectively. Based on these data, it can be seen that the system plant had a longer leaf length than the control plant.

Based on the plant growth data above, it can be seen that plants given additional light with LED grow lights experience faster growth than plants without LEDs. This occurs because LED grow lights are able to replace sunlight at night for photosynthesis.

According to Huché-Thélier et al. (2016), leafy plants require wavelengths for

photosynthesis in the visible light spectrum of 500-600 nm. This light spectrum wavelength can be obtained from LED grow lights. In theory, pak choy plants with additional lighting from LEDs will experience faster growth than plants without LEDs. LED plants experience a longer photosynthesis period because the light spectrum from LEDs can replace sunlight as the main component of the photosynthesis process in plants (Figure 13). The LED light spectrum refers to the electromagnetic wavelength of light produced by a light source to encourage plant growth. For photosynthesis, plants use light in the PAR (photosynthetically active radiation) region with wavelengths (400nm-700nm) measured in nanometers (nm) (Wu et al., 2024).



Figure 13. Plants with LED lighting

CONCLUSION

This research successfully designed a solar panel-based LED grow light system for application in *greenhouses* with *Hydroponic Tower System* (HTS), effectively providing additional lighting at night. The solar panels used have an average energy conversion efficiency of 20%, with stable peak power achieved between 11:00-12:00 WIB. The maximum input power produced by the solar panels is 3045.07watts with a maximum light intensity of 1180.26W/m², indicating good solar panel performance in supporting the system's energy needs. The addition of LED grow lights has been shown to increase the growth of pak choy plants, indicated by significant T-test results on the parameters of plant height, leaf length, leaf width, and number of leaves compared to control plants. Overall, this system has great potential to be implemented in urban agriculture as part of a sustainable agricultural solution based on renewable energy.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to the Laboratory of Instrumentation and Control, Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, for providing laboratory facilities and technical support during this research.

REFERENCES

- Abu Hatab, A., Cavinato, M. E. R., Lindemer, A., & Lagerkvist, C. J. (2019). Urban sprawl, food security, and agricultural systems in developing countries: A systematic review of the literature. *Cities*, 94, 129-142. <https://doi.org/10.1016/j.cities.2019.06.001>
- Al-Kodmany, K. (2018). The vertical farm: A review of developments and implications for the vertical city. *Buildings*, 8(2). <https://doi.org/10.3390/buildings8020024>
- Al-Shamani, A. N., Alghoul, M. A., Elbreki, A. M., Ammar, A. A., Abulkhair, H. A., & Sopian, K. (2016). Design and performance evaluation of a photovoltaic powered greenhouse system. *Renewable and Sustainable Energy Reviews*, 59, 873-884. <https://doi.org/10.1016/j.rser.2016.01.021>
- Arifin, B., Achسانی, N.A., Martianto, D., Sari, L.K., & Firdaus, A.H. (2019). The future of Indonesian food consumption. *Indonesian Journal of Economics*, 8(1), 71-102. <https://doi.org/10.52813/jei.v8i1.13>
- Barbosa, G. L., Gadelha, F. D. A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., & Halden, R. U. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International Journal of Environmental Research and Public Health*, 12(6), 6879-6891. <https://doi.org/10.3390/ijerph120606879>
- Bantis, F., Koukounaras, A., Siomos, A. S., Fotelli, M. N., & Kintzonidis, D. (2020). Bichromatic red and blue LEDs during healing enhance the vegetative growth and quality of grafted watermelon seedlings. *Scientia Horticulturae*, 261, Article 109000. <https://doi.org/10.1016/j.scienta.2019.109000>
- Chatterjee, A., Ghosh, P., Winkler, B., V. V., Debnath, S., Cichocki, J., Trenkner, M., Vanicela, B., Riethmueller, C., Walz, M., Chandra, S., & Pal, H. (2025). Demystifying the integration of the hydroponics cultivation system, reinforcing bioeconomy and sustainable agricultural growth. *Scientia Horticulturae*, 341, Article 113973. <https://doi.org/10.1016/j.scienta.2025.113973>
- Fan, X.-X., Xu, Z.-G., Liu, X.-Y., Tang, C.-M., Wang, L.-W., & Han, X.-L. (2013). Effects of light intensity on the growth and leaf development of young tomato plants grown under a combination of red and blue light. *Scientia Horticulturae*, 153, 50-55. <https://doi.org/10.1016/j.scienta.2013.01.017>
- Faust, J. E., Logan, J., & Heins, R. D. (2005). Daily light integral: A research review and high-resolution maps of the United States. *HortScience*, 40(7), 1825-1829. <https://doi.org/10.21273/HORTSCI113144-18>
- Gholami, M., Arefi, A., Hasan, A., Li, C., & Muyeen, S. M. (2025). Enhancing energy autonomy of greenhouses with semi-transparent photovoltaic systems through a comparative study of battery storage systems. *Scientific Reports*, 15(1), Article 2213. <https://doi.org/10.1038/s41598-025-85418-z>
- Hassanien, R. H. E., Li, M., & Dong Lin, W. (2016). Advanced applications of solar energy in agricultural greenhouses. *Renewable and Sustainable Energy Reviews*, 54, 989-1001. <https://doi.org/10.1016/j.rser.2015.10.095>

- Huché-Théliér, L., Crespel, L., Gourrierc, J. Le, Morel, P., Sakr, S., & Leduc, N. (2016). Light signalling and plant responses to blue and UV radiations: Perspectives for applications in horticulture. *Environmental and Experimental Botany*, 121, 22-38. <https://doi.org/10.1016/j.envexpbot.2015.06.009>
- Mitchell, C. A., Both, A. J., Bourget, C. M., Burr, J. F., Kubota, C., Lopez, R. G., Morrow, R. C., & Runkle, E. S. (2015). LEDs: The future of greenhouse lighting. *Chronica Horticulturae*, 55(2), 6-12.
- United Nations. (2019). *World urbanisation prospects: The 2018 revision* (ST/ESA/SER.A/420). <https://population.un.org/wup/assets/WUP2018-Report.pdf>
- Parker, G. G., Fitzjarrald, D. R., Cibelle, I., & Sampaio, G. (2019). Consequences of environmental heterogeneity for the photosynthetic light environment of a tropical forest. *Agricultural and Forest Meteorology*, 278, Article 107661. <https://doi.org/10.1016/j.agrformet.2019.107661>
- Pereira, J. (2025). Lighting strategies in vertical urban farming for enhancement of plant productivity and energy consumption. *Applied Energy*, 378, Article 124669. <https://doi.org/10.1016/j.apenergy.2024.124669>
- Pennisi, G., Orsini, F., Landolfo, M., Pistillo, A., Crepaldi, A., Nicola, S., De Pascale, S., & Gianquinto, G. (2019). Optimal photoperiod and light intensity for indoor cultivation of leafy vegetables. *Scientia Horticulturae*, 249, 96-104. <https://doi.org/10.1016/j.scienta.2019.01.013>
- Putri, R. E., Putri, I., & Hasan, A. (2025). Design and performance testing of a solar power generation system (SPGS) for a smart greenhouse with tower hydroponic support. *International Journal of Energy Production and Management*, 10(2), 165-173. <https://doi.org/10.18280/ijepm.100201>
- Putri, R. E., & Jatiarum, S. A. (2025). Optimising pakcoy (*Brassica rapa* L.) growth in a smart greenhouse: Harnessing IoT for temperature and humidity control through tower farming systems. *IOP Conference Series: Earth and Environmental Science*, 1477(1), Article 012047. <https://doi.org/10.1088/1755-1315/1477/1/012047>
- Putri, R. E., & Agus, N. P. (2025). Development of automatic watering system using verticulture method on pakcoy (*Brassica rapa* L.) based Internet of Things (IoT). *AIP Conference Proceedings*, 3223(1). <https://doi.org/10.1063/5.0243748>
- Putri, I., Putri, R. E., & Pramana, F. A. (2023, June). Performance test of solar power plant as a source of electricity in mini greenhouse. *IOP Conference Series: Earth and Environmental Science*, 1182(1), Article 012021. <https://doi.org/10.1088/1755-1315/1182/1/012021>
- Skoplaki, E., & Palyvos, J. A. (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar Energy*, 83(5), 614-624. <https://doi.org/10.1016/j.solener.2008.10.008>
- Villalva, M. G., Gazoli, J. R., & Filho, E. R. (2009). Comprehensive approach to modelling and simulation of photovoltaic arrays. *IEEE Transactions on Power Electronics*, 24(5), 1198-1208. <https://doi.org/10.1109/TPEL.2009.2013862>
- Wu, B. S., Mansoori, M., Schwalb, M., Islam, S., Naznin, M. T., Addo, P. W., MacPherson, S., Orsat, V., & Lefsrud, M. (2024). Light emitting diode effect of red, blue, and amber light on photosynthesis and plant growth parameters. *Journal of Photochemistry and Photobiology B: Biology*, 256, Article 112939. <https://doi.org/10.1016/j.jphotobiol.2024.112939>

- Xin, P., Li, B., Zhang, H., & Hu, J. (2019). Optimisation and control of the light environment for greenhouse crop production. *Scientific Reports*, 9(1), 1-13. <https://doi.org/10.1038/s41598-019-44980-z>
- Yusuf, A. G., Al-Yahya, F. A., & Saleh, A. A. (2025). Optimising greenhouse microclimate for plant pathology: Challenges and cooling solutions for pathogen control in arid regions. *Frontiers in Plant Science*, 16, 1-15. <https://doi.org/10.3389/fpls.2025.1492760>
- Zou, J., Luo, S., Shi, M., Wang, D., Liu, W., Shen, Y., Ding, X., & Jiang, Y. (2025). Effects of different light intensities on lettuce growth, yield, and energy consumption optimisation under uniform lighting conditions. *PeerJ*, 13(3), 1-17. <https://doi.org/10.7717/peerj.19229>